



Nordic Industrial Fund
center for innovation and commercial development

ProSheet

**Prototyping and low volume
production of sheet metal components**

Research report

NI Project number: 03028

Lotta Lamminen

Boel Wadman

Rein Küttner

Torgeir Svinning



1.	Introduction	3
2.	Sheet metal forming for low volume production	4
2.1.	Low series tooling	4
2.2.	Multi-process equipment	5
2.3.	Flexible forming media	6
3.	Incremental forming	8
3.1.	A literature overview	8
3.1.1.	Experimental studies	9
3.1.2.	Simulation of the process	10
3.2.	Dieless NC Forming	11
3.2.1.	Principal	11
3.2.2.	Limitations	14
3.2.3.	Economics of incremental sheet metal forming	17
3.2.4.	Variations of incremental forming	20
3.2.5.	Applications	21
4.	An application - Low volume production of aluminium boats	21
5.	Summary	22
	References	23
	Attachments	25

1. Introduction

”ProSheet – Prototyping and low volume production of sheet metal components” has been funded by Nordic Industrial Fund. The project started on April 1st 2003 and lasted until the end of December 2003. The project aimed to clarify the situation of sheet metal forming technologies for low volume production in the Nordic countries and EU and map the industrial demands on the field. The objective was to give Nordic industry information on available methods to produce low volume sheet metal products. The focus has been on cost efficient methods that are flexible enough to produce different product geometries with a short lead times.

Manufacturing industry is changing rapidly. Prototyping with rapid manufacturing technologies is a part of the everyday business in many companies and prototypes are used efficiently as part of the production development process. As customers demand more tailored products, and production series in many cases become smaller, new methods for low volume production and prototyping are required.

Sheet metal forming has traditionally been a technology area where prototyping has been extremely expensive and efficient options for low volume production have been limited. Producing complicated geometries has also been difficult.

The sheet metal forming technologies have developed rapidly recently. New methods enable forming of complicated geometries, and short series with low cost. Some of the methods are still quite new, some have been used for a while, but the industry’s awareness of these methods should be increased.

This report describes the state-of-the-art of sheet metal forming technologies for low volume production, and some ideas from the project group of potential applications in Nordic sheet forming industry.

The steering group of the ProSheet project has been:

Lotta Lamminen, project leader, Helsinki University of Technology, Finland

Boel Wadman, IVF, Sweden

Torgeir Svinning, SINTEF, Norway

Rein Küttner, Tallinn Technical University, Estonia

2. Sheet metal forming for low volume production

Production in low series and small batches induces higher demands on the production system as a whole. High flexibility (fast changeover) and short decision times are important. Apart from adapting the organization to low volume, the right forming process must be chosen.

Regarding the forming process, the following guidelines can be used for efficient low volume production:

- Reduced lead-time for each product, and reduced changeover time between products
- Reduced time and cost for development and manufacturing of tool
- Flexible production units and production lines
- Lower time between different products by using flexible tooling, e.g. incremental forming or fluid forming
- A flexible and common control and materials handling system for each unit and for the whole production line.

2.1. Low series tooling

Lower material cost and shortened production time can reduce the cost of tooling. Tool materials can be cast iron, aluminium and cast Zn-alloys with high machinability. For prototypes and mild steel, also polymers and wood can be used as tooling materials.

Rapid tooling methods are for example:

- Lamellar tools, laser cut or precision cut layers that are joined by bolting and/or adhesives
- Electroplated Ni-surface with backing of concrete or polymer (Figure 1)
- Direct fabrication methods: Laser sintering, high speed milling, casting

Efficient systems for design and 3D modelling of tools are important.



Figure 1 Electroplated Ni surface tool from Giant Tools A/S, Denmark

2.2. Multi-process equipment

Most sheet metal products are subject to additional processing to the forming operation. This may be cutting before or after forming, various joining methods, processes for making holes, and so on. In high volume production this may be special secondary processing units included in the production line, e.g. welding cells, flying saws, hole punching, or machining operations of various kinds. For low series one has to rely on applying various pieces of production equipment, each of them being flexible enough to be reprogrammed according to a changing product spectrum. The importance of having the same kind of control system for the combined units, i.e. the production line, is obvious. Another possibility is where the production unit in itself is capable of performing various tasks.

One example is *laser cutting and forming* (Figure 2). A CO₂-laser can be used both to cut the sheet material, but also to form simple geometries. The heat induced by the laser beam bends the sheet to the calculated geometry. Metals with low thermal conductivity, i.e. stainless steel, are more easily deformed. Both thin and thicker gauges can be formed; the method was originally used for tube bending in the ship building industry.

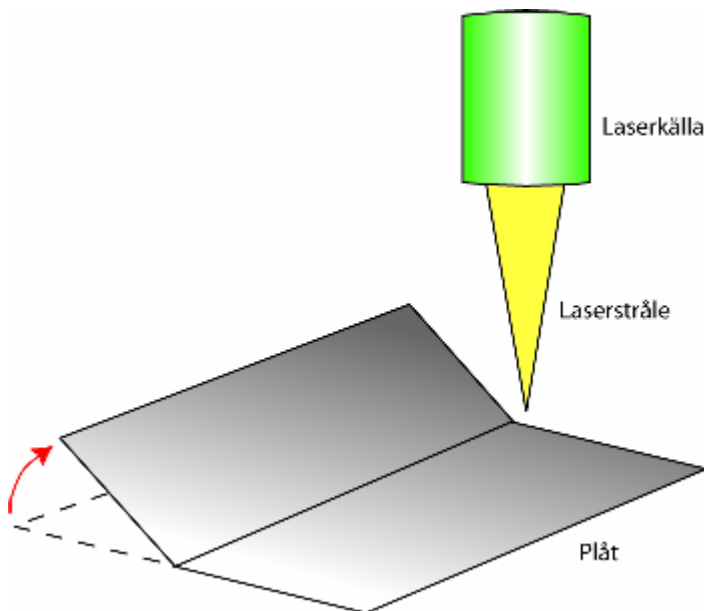


Figure 2 Laser forming where a sheet is bent by the heat

The method is under development; primarily considering models to predict the heating passes needed for the desired forming geometry. Laser optics to form circular and double-curved shapes were also recently developed. In Figure 3 a test product is shown.



Figure 3 Test product produced by laser welding, punching

Another process, similar to laser forming, where heating is used to generate internal stresses in the material and by that causing the sheet to bend, is *plasma jet forming*.

Roll forming is a method where several process steps can be included in the same line. By “start - stop” rolls or “flying tools” also clinching, punching and welding can be performed at different stages of the sequential bending operation. Special rolls may also be applied to modify the surface of the profile, e.g. by “imprinting” a specified pattern. The tools for roll forming have a lower cost than complicated press tools, but a higher cost than press-brake tools, which makes the method applicable for medium-sized series production of beams and elongated panels.

2.3. Flexible forming media

Reducing the number of tools is another way of lowering the part cost. In “rubber pad forming” one tool is replaced by a thick rubber mat which deforms during pressing. This is used for example for coining and embossing, where only a small amount of metal is needed to flow into the formed region. To obtain both flexible die and stamp the multi-point method is investigated in China. It involves several hydraulic cylinders working against each other to shape a detail. The early try-outs gave rather poor surface properties, which were ameliorated by an intermediate sheet. Different modes of multi-point forming are shown in Figure 4.

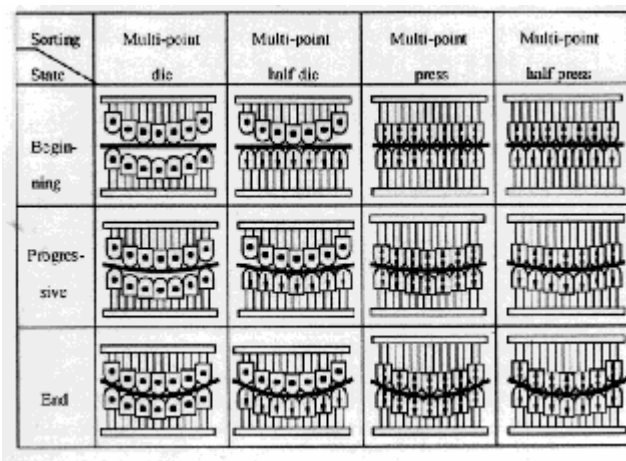


Figure 4 Different modes of multi-point forming, where the die pins can be either passive or produce an active pressure towards the stamp.

Fluid cell forming

Several hydro-forming methods use a fluid to replace one of the two press tools. A method frequently used for prototypes is fluid-cell forming (Figure 5) or flex forming.

One rigid tool is used for simple geometries. The blank is formed between the tool and a rubber diaphragm that is pressurized with castor oil up to 1600 bar. The blank is not in contact with the forming oil.

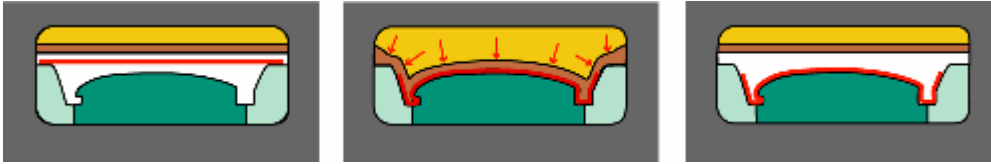


Figure 5 Fluid cell forming of detail with undercut. The sheet (red) is pressed towards a rigid tool by a rubber membrane (orange) filled with castor oil (yellow).

Process characteristics:

- Large details, up to maximum press table size: 1.3 x 2.5 m.
- Surface roughness: Depending on tool surface, normal is $R_a = 6 \mu\text{m}$.
- Cycle time: Approximately 5 minutes, independent of product size. (If several tools exist, 2 - 5 smaller products can be formed simultaneously.)
- Time from CAD to product: Approximately 4 weeks, at least 4 days (with Rapid-tooling)
- Tool cost: Depending on size, 2000-5000 Euro
- Change over time between products: 1 - 8 hours, depending on tool complexity.
- Cost of production line: 70 000 Euro – 1 000 000 Euro

Geometric limitations:

- Inner (concave) radii are defined by the forming pressure, and cannot reach smaller values than the sheet thickness.
- The corner radii and edge radii are dependent on the product height. The lower the product height, the smaller radii can be formed.

When to chose this method:

- Low volume production, where the lower tool cost can balance the higher cycle time
- For large products with low height and small radii
- Small radii products: Mild steels and thin gauges
- Double-curved shapes and flat details, that need high pressure forming to obtain lower springback
- Negative radii can be formed if the tool can be divided and withdrawn from the detail.

3. Incremental forming

3.1. A literature overview

A large number of papers are devoted to sheet metal forming processes. However, a quite limited amount of literature dealing with incremental sheet metal forming can be found. Recently, some papers concerning techniques of incremental sheet metal forming have been published by researchers from Japan and South Korea.

An approximate deformation analysis for the incremental bulging of sheet metal using a ball roller is developed [1]. The incremental bulging method has been applied for non-symmetric shallow shells. In [1] the plane-strain deformation model has been proposed. This model makes an approximation that the sheet metal in contact with the ball roller stretches uniformly. The friction at the interface between tool and sheet, the plane anisotropy and Bauschinger effect of the sheet material are neglected. The closed form expressions for the uniform strains and of the deformed shell are pointed out. The tensile force is determined from the condition that the un-deformed part is rigidly moved by the stiffness of the shell. The results, obtained by the approximate deformation analysis, FEM analysis and experiments are in good agreement. However, the complete incremental bulging operation has not been modelled in [1].

Vertical wall surface forming of rectangular shell using multistage incremental forming is studied [3]. A method of calculating for the approximate distribution of thickness strain and the maximum bulging height has been proposed using a plane-strain deformation model with a constant strain gradient. In [4] a mapping relationship between the blank and its formed specimen under the condition of even strain is obtained and the following characteristics of the incremental forming process are pointed out:

- the sheet is formed according to a given locus
- the deformation of the sheet is point-by-point
- the deformation of every step is small.

Two reasons leading to the unevenness of the wall thickness distribution are discussed in details:

- because of the effect of spring-back, the practical deformation of the centre of the specimen is smaller than that of the boundary, when there is the same value of the deformation
- for work-pieces for which the distances from the centre of the sheet are equal, the later forming parts have certain displacement and working hardness before the head tool bulges it. Thus, this part has a smaller plastic deformation under the same value of deformation.

The solutions for the both problems are proposed:

- Since the boundary of the sheet is fixed and the centre is free, the stiffness of the boundary is large and the stiffness of the centre is small. Therefore, every incremental step should be considered as a priority in the sequence from small stiffness to large stiffness. Thus the plastic deformation of the centre can be increased and the plastic deformation of the boundary can be decreased, which improves the degree of evenness of the deformation.
- The amount of the deformation should be small, which makes the sheet approach the final shape of the specimen integrally and evenly. Thus, the working hardness of the later forming area can be decreased. Actually, the sequence of forming of the work-pieces should be alternated: the area that is formed first in this incremental step should be formed later in the next incremental step.

A simplified FEM model is developed in [5] assuming that all deformation occurs only by shear deformation. The intermediate shape was determined from the predicted thickness strain so as to

distribute the deformation uniformly. Next the sheet metal has been deformed by a double-pass forming undergoing the calculated intermediate shape. The proposed method has been applied to the analysis of an ellipsoidal cup and a clover cup.

The formability in incremental forming of sheet metal is studied in [6][7][8]. In [6] a forming tool containing a freely rotating ball was developed. The results observed in the tests were examined by grid measurement and finite element analysis. A unique forming limit curve was obtained. It was pointed out that the forming limit curve is quite different from that in conventional forming. It appears to be a straight line with a negative slope in the positive region of the minor strain in the forming limit diagram. It was also observed that the cracks occur mostly at the corners (due to greater deformation at the corners). In [7] the effects of process parameters (tool size, feed rate, plane-anisotropy) on formability are studied. The formability of an aluminium sheet under various forming conditions is considered in [8]. Complex shapes (octagonal cones, stepped shape, bucked shape) were produced with the proposed technique.

Different die technologies and dieless technologies for trial and small lot production are compared in [9]. The principles and features of the recently developed incremental forming processes are overviewed in [10][11]. In [11] a special attention is paid to cone metal spinning and flow-forming.

3.1.1. Experimental studies

Many experimental papers are concerned with incremental sheet metal forming. Sheet metal bulging with a spherical roller is considered in [1], [3], [12] and [13], hammering in [14] and [15], spinning in [16] and [17], peen forming in [18] and bulging with an elastic tool in [19]. Incremental forming of sheet metal with a single point tool is studied in [20], [21] and [22]. Reflective surfaces of automobile headlights were prototyped in [22]. A new flexible sheet metal forming system for fabricating micro-three-dimensional structures of foil metallic materials of less than 10 nm in thickness has been developed in [23].

Most authors used in their experimental study on incremental forming regular 3 axis milling machine. Figure 6 presents the incremental sheet metal forming process.

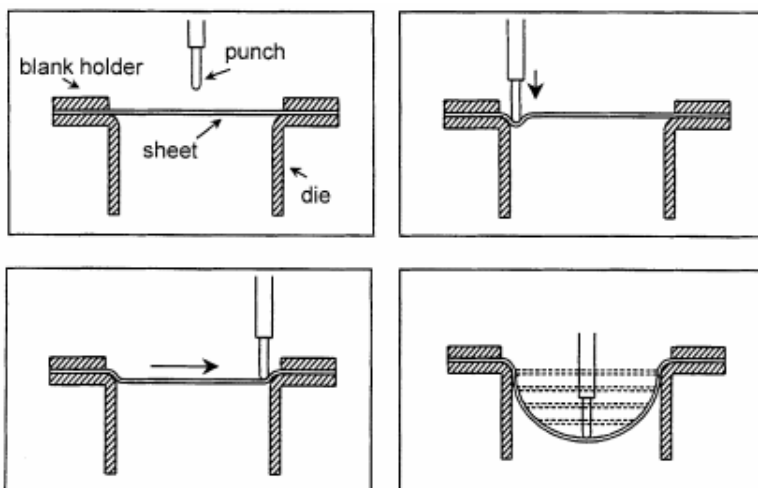


Figure 6 Schematic diagram of the incremental sheet metal forming process [4].

Iseki & Nagawa studied multistage forming using special tooling for straightening after incremental forming walls (Figure 7) and bottom surfaces (Figure 8) of the formed part.

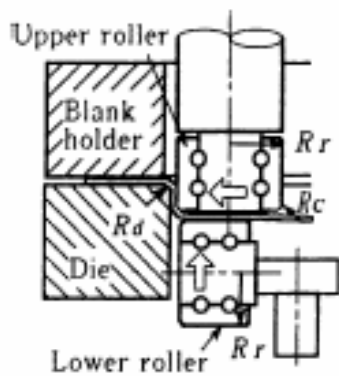


Figure 7 Vertical wall surface forming [3].

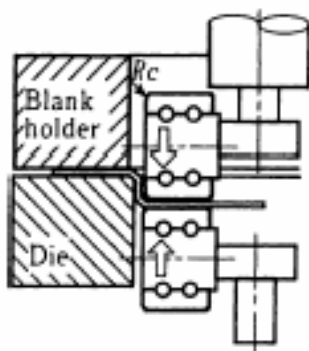


Figure 8 Bottom surface forming [3].

3.1.2. Simulation of the process

It is difficult in general to predict the thickness strain distribution of the initial state of a deformation after the accumulation of numerous incremental deformation passes. One option to calculate the thickness strain during the whole deformation process is by using finite element analysis (FEA). Nevertheless, FEA has some difficulties when applied to the incremental sheet metal forming process. The most critical problem is the large number of calculation steps, which means very long time for calculation. Compared with the general sheet metal forming processes, the incremental sheet metal forming process has a simple deformation mechanism but the deformation path of its moving tool in this process is much longer. If the entire process has to be analyzed, too much time is required. [5]

In their study, Kim & Park [6],[7] used a commercial FEA code, PAM-STAMP produced by ESI Group [24], for the analysis of sheet metal incremental forming. PAM-STAMP is a dynamic explicit program that is developed specially for simulation of sheet metal forming processes. It was used to analyze the deformation that occurred in the straight groove test. The results of this analysis provided enough information to understand the trend of deformation. [7] In their simulation, the model included tool, blank holder, sheet (blank) and die, which all were modeled using 3D shell elements. The tool was moved stepwise vertically by 0,5 mm. After each vertical step it moved on horizontal plane along rectangular path. As a result of analysis, thickness distributions and strains of sheet were obtained.

Iseki used in his study [1] Abaqus, developed by Abaqus Inc [25], to compare the experimental results with the theoretical results of the finite element analysis and approximate deformation analysis of incremental bulging process. In the article it is not said whether author used implicit or explicit finite element code as Abaqus supports them both. Finite element model was made using 3D shell elements.

Hemispherical tool was moved stepwise vertically. After each vertical step it moved on horizontal plane along rectangular path. It was found that FEA results were in good agreement with physical tests.

Although, more scientific papers describing simulation of the incremental forming process were not available, information from papers concerning simulation of other forming processes was found useful, as the physical phenomena of deforming is similar. Below are mentioned some more frequently used FEA systems.

Srinivasan et al. [26] used LS-DYNA, developed by Livermore Software Technology Corp. [27] to simulate tube hydro-forming process. LS-DYNA is explicit FEA code that supports adaptive remeshing and will refine the mesh during the analysis, as necessary, to increase accuracy and save time.

Koc & Altan [28] and Hwang & Altan [29] used DEFORM, developed by Scientific Forming Technologies Corporation [30], for simulation of tube hydro-forming process. DEFORM is a process simulation system designed to analyze the three-dimensional flow of complex metal forming processes. It is used relatively widely in metal forming industry.

Duan & Sheppard [31] used MSC.MARC, developed by MSC.SOFTWARE Corporation [32], for simulation and optimization of metal forming process. MSC.MARC is implicit FEA system for general purpose nonlinear analysis. Includes automated 3D contact and automated mesh enrichment.

Both, 2D and 3D simulations can be valuable for the research. It is obvious that 3D simulations are the desired choice, but they are also much more resource intensive. It is important to emphasize, that the simulation of the full incremental forming process can be much too resource intensive to be modeled with FEA, so high simplification level has to be used.

3.2. Dieless NC Forming

3.2.1. Principal

Dieless NC Forming is a cold forming technology that is developed in Japan for the needs of automotive industry. It has been commercialised by Japanese company Aimono Corporation. Dieless NC Forming is a numerically controlled incremental forming process that can form various materials into complex shapes. The method allows forming without large and expensive dies, using only a simple support tool under the formed piece. This makes the method very cost effective. Dieless NC Forming is an alternative manufacturing method to small lot production and prototyping.

The geometry of the piece is converted from CAD data through CAM to NC data. It is downloaded to the machine controllers' 3-axis Servo system, as shown in Figure 9. The equipment used for dieless NC forming is shown in Figure 10. The blank sheet is clamped to a square workholder such that there is no draw in from the binders. Z-tool is actuated in the Y and Z direction and the workholder is counterbalanced to the vertical movement of the tool and is actuated in the X direction.

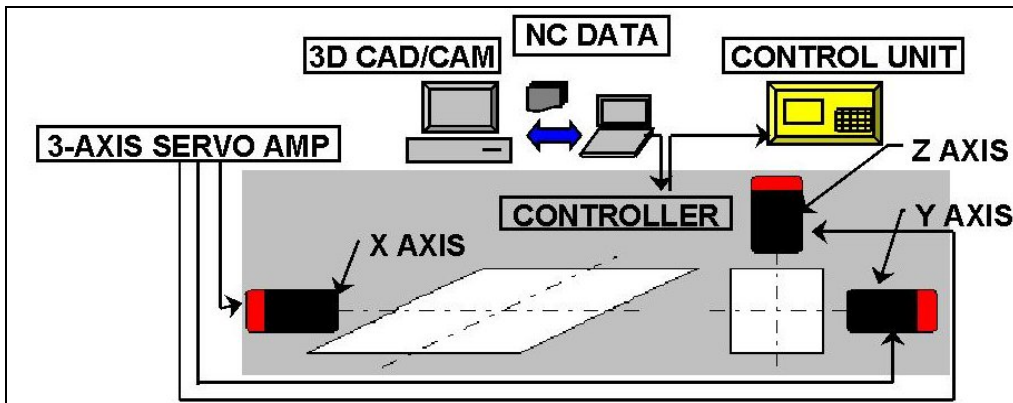


Figure 9 The control system of Dieless NC Forming machine. (Amino Corporation)

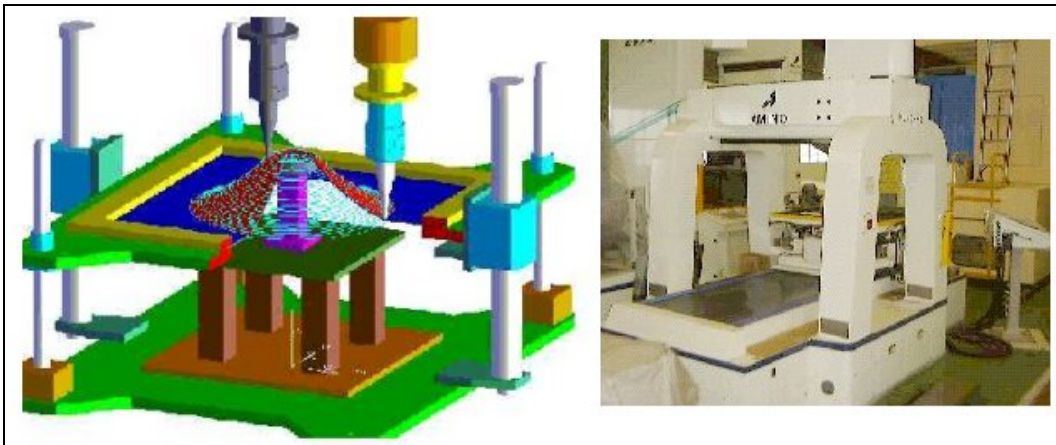


Figure 10 Equipment for Dieless NC Forming process

The blank sheet is attached to a blank holder. The blank holder moves in vertical direction according to descending of Z-tool and along X- and Y-planes. Some machines only allow moving along X-plane. The X- and Y-plane movements are synchronised with tool movements to produce the desired form on the sheet.

The support tool is placed under the workholder and the blank sheet is moulded against the support tool. Moving tool, or Z-tool, slides on the surface of the sheet and presses the sheet into desired form. The Z-tool is computer controlled. The forming principle is shown in Figure 11.

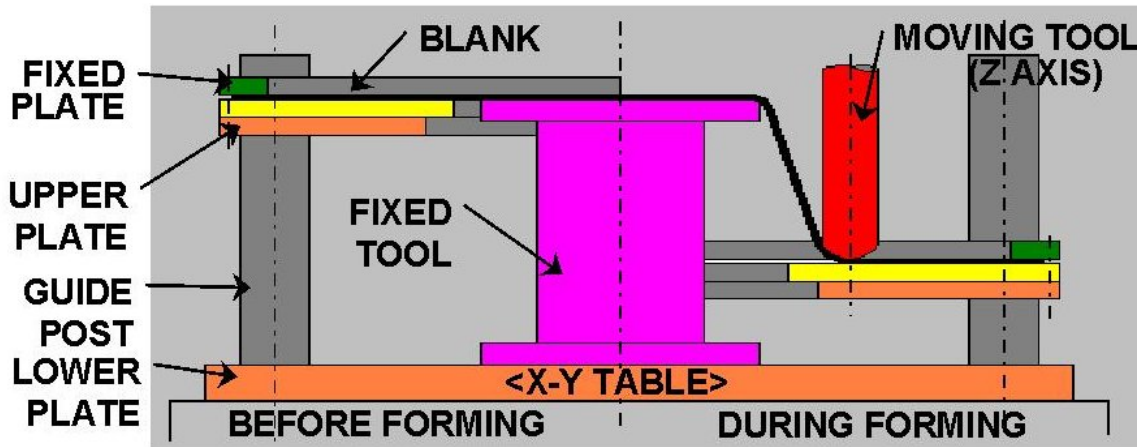


Figure 11 Principal of Dieless NC Forming (Amino Corporation)

Forming starts on the top of the piece, where also the support tool is placed. The Z-tool makes a round path around the support tool and after one round, lowers itself down for defined pitch and continues forming. The tool path as well as the vertical pitch are defined by the conversion software based on the CAD-model of the product. The tool changes the moving direction after each round to prevent material twisting around the Z-axis of the product. The forming process is illustrated in Figure 12.

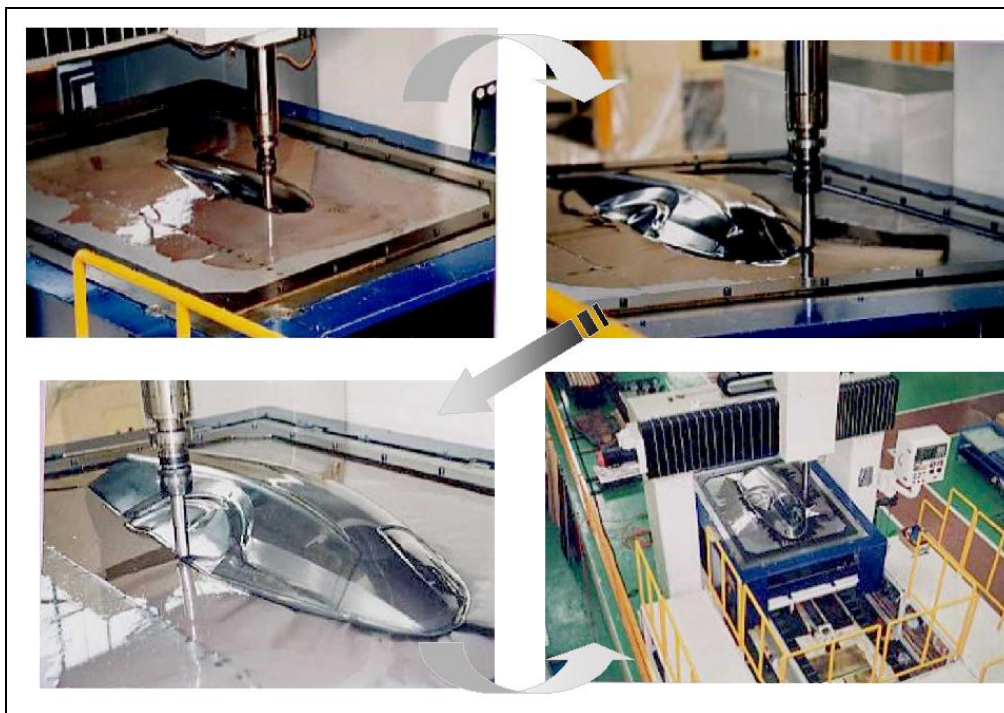


Figure 12 Dieless NC forming process

The Z-tool is made of hardened steel and the tip of the tool is spherical (Figure 13). The tool slides on the surface of the formed sheet and causes the stretching and bending of the sheet. The minimum diameter of the tool is 6 mm. The tool diameter affects the surface quality and larger diameter results smoother surface as the toolmarks are smaller. The forming force depends on the sheet thickness and material. The force has to exceed the yield strength to create plastic deformation.



Figure 13 Z-tools (Ø20 mm and Ø10 mm)

The forming process requires lubrication on the surface of the sheet. Lubrication decreases the friction between the tool and the sheet and absorbs the heat caused by deformation. The amount of the lubricant depends on the material and thickness of the sheet. Forming of stainless steel and thick sheets require more lubricant than thick aluminium sheets.

3.2.2. *Limitations*

Dieless NC Forming is suitable for one-piece and low volume production. It can also be used as a prototyping method for sheet metal products produced in large series. The maximum production capacity of the Dieless NC Forming machine is about 500 pieces a month, varying widely on the size and geometry of formed products. The method is slow when compared to for example deep drawing, and it is not competing with traditional forming methods. There are still some limitations with the method, described below.

3.2.2.1. *Geometry*

Dieless NC Forming is a suitable method for producing complicated three-dimensional forms. The product geometry is rather free, but there are few limitations with it, depending on the sheet thickness and the equipment used.

The tool size defines the minimum rounding radius, which is half of the tool diameter. The tool size depends on the sheet thickness, because small and thus thin tools are not strong enough for required forming forces with thick sheets. As the smallest tool used has a diameter of 6mm, the minimum rounding radius is 3 mm. However, the machine manufacturer recommends that the smallest rounding radius used should be 5 mm.

The tool operates only in Z-direction. This makes inward bent forms impossible. The wall angle is limited by the sheet thickness. The more the sheet is bent, the more it thins, as shown in Figure 14. The material formability affects the minimum wall angle as well. Hardened sheet shears off in the bending if the wall angle is too steep. The forming tests have resulted that minimum wall angle for steel is approximately 25°, for pure aluminium 20° and for heat-treated aluminium 30-35°.

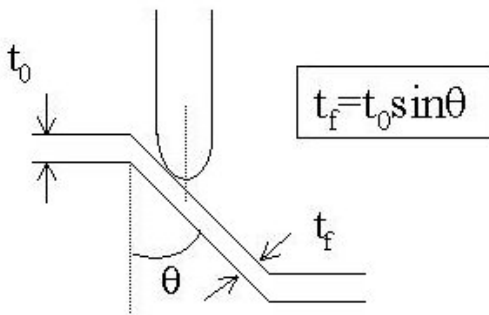


Figure 14 The correlation between sheet thinning and bending. The final thickness (t_f) depends on initial thickness (t_0) and bending angle (θ). [33]

The product geometry defines the need and complexity of the support tool. Simple tool can be used in products where the walls does not include horizontal surfaces. Then the sheet can be supported on the highest point of the product and form the walls without any extra support. Examples of this kind of products and support tool are shown in Figure 15.



Figure 15 Simple support tool and parts made with it



Figure 16 Bath tub and the support tool.
The bath tub is appr. 1500 mm x 1000 mm.

If the product has planar surfaces that has to be accurate, they have to be supported from below. The Z-tool can be programmed to form a planar surface also without support tool beneath, but this easily results sloping. When the forming proceeds to the point where the wall bends again, the sheet bends instead of stretching and the planar surface twists, if nothing supports the edge. Figure 16 shows a bath tub formed with Dieless NC Forming and the support tool used in the forming. In the support tool all the planar surfaces and rounding radii are supported, while the rest of the walls are formed freely. The more complex the part is, the more detailed the support tool has to be. In some cases the support tool can be as detailed as the final product.

3.2.2.2. Product size

The maximum product size is defined by the machine size. There are five different size of machines for research and production use. The technical data of these machines is shown in Table 1.

The maximum sheet thickness is different for each machine. The critical factor is the force needed for forming. As the yield strength varies according to the material used, the forming force and thus the

maximum sheet thickness depends on the material and the machine used. As can be seen in Table 1, the possible material thickness in forming is 0,5...2 mm for stainless steel and 0,5...4 for aluminium.

Table 1 Technical data of Dieless NC Forming machines

		Research use		Commercial use		
		DLNC-RA	DLNC-RB	DLNC-PA	DLNC-PB	DLNC-PC
Maximum blank size (mm)		400X400	600X600	1100X900	1600X1300	2100X1450
Maximum forming size (mm)		300X300	500X500	1000X800	1500X1200	2000X1350
Maximum forming depth (mm)		150	250	300	400	500
X-axis stroke		330	550	1100	1600	2100
Y- axis stroke		330	550	900	1300	1450
Z- axis stroke		200	300	350	450	550
Maximum work holder size (mm)		500X500	750X950	1300X110	1800X1500	2300X1650
Maximum sheet thickness	Stainless steel	0,5-1	0,5-1	0,5-2	0,5-2	0,5-2
	Aluminium	0,5-3	0,5-3	0,5-4	0,5-4	0,5-4

Dieless NC Forming enables greater draw ratio than for example deep drawing. In deep drawing the material stretches and accumulates on the bottom of the drawn piece, because the geometry does not allow the material to move away from under the tool in the end of the forming. This creates bumps on the bottom of the drawn cup. In Dieless NC Forming the forming direction is different and the geometry does not prevent the material moving. When the forming starts from the top of the piece and from the center of the sheet, the material stretches and moves away from under the tool as the forming proceeds. This enables greater draw ratio.

3.2.2.3. Surface quality

The Z-tool leaves marks on the formed surface on each forming round. The tool marks can be decreased by using tool with large diameter and decreasing the forming pitch. Smaller pitch leads to longer forming time, so there is a trade-off between production time and surface quality. If the pitch is smaller than 0.01 mm, the material is formed several times on the same spot, and the material will strain harden. This results easily tearing of the sheet. Strain hardening also increases the stress in the sheet and the form can be twisted.

Large, slightly curved surfaces are difficult to form. The tool marks are clear, because the horizontal movement on each pitch becomes large as the curve is very gentle. The tool marks can be prevented by using a sacrificing sheet on the top of the actual sheet in the forming process. Then the sacrificing sheet takes the tool marks on itself but transfers the geometry to the actual sheet below. The geometry is not as accurate as it would be in the direct tool contact, but the surface quality is better. The actual sheet can then be formed again without using a sacrificing sheet and sharpen the details in the product. This results often satisfying quality.

Hirt, Junk and Wituski [33] have studied how forming affects the surface roughness. The forming process smooths the surface on the forming size of the product, but the surface roughness on the other side of the sheet increases relatively. As the tool diameter increases, the surface roughness decreases. The surface roughness can also be decreased by changing the forming direction on each round and decreasing the forming pitch. As all the parts of the products are not formed as much as others, some parts staying completely unformed, the surface roughness is not constant over the product surface. Planar surfaces are always unformed, thus the surface roughness remains the same as the surface roughness of the original material. Steep wall angles require more forming and small pitch, thus the surface roughness is decreased during the forming.

3.2.2.4. *Materials*

The Dieless NC Forming has been tested with sheets of carbon steel, rapid steel, stainless steel, alloyed aluminium, titanium and coated steels. The best results were achieved by forming steel, in regard of final geometry and springback. Rapid steel is also easy to form, but it has strong springback. Stainless steel requires strong forming force, which leads to thinner sheets than when forming normal steel. Stainless steel also has strong springback and product geometry is easily twisted during the forming. Stainless steel requires lot of lubrication during the forming, and the forming speed has to remain low.

The formability of aluminium depends on the alloy used. Pure aluminiums A1000 and A1100-0 are easy to form. A6XXX-alloys, that include magnesium and silicon, has poor formability and has strong springback. Pure aluminium is recommended for forming, if it is suitable for the product.

Titanium heats up during the forming and tends to blister. Forming coated sheets is difficult, because the coating comes easily off under the forming tool. If the sheet can be formed on the reverse side, the coating on the face side remains untouched.

It is also possible to form perforated steel using Dieless NC Forming. Then the minimum wall clearance is about 45° . The holes stretch as the sheet stretches, but when the clearance angle and rounding radii are kept large, the sheet does not tear during the forming.

3.2.3. *Economics of incremental sheet metal forming*

Incremental sheet forming costs has been compared with costs of deep drawing. The comparison has been made using a simple example piece, that is shown in Figure 17 and Figure 18.

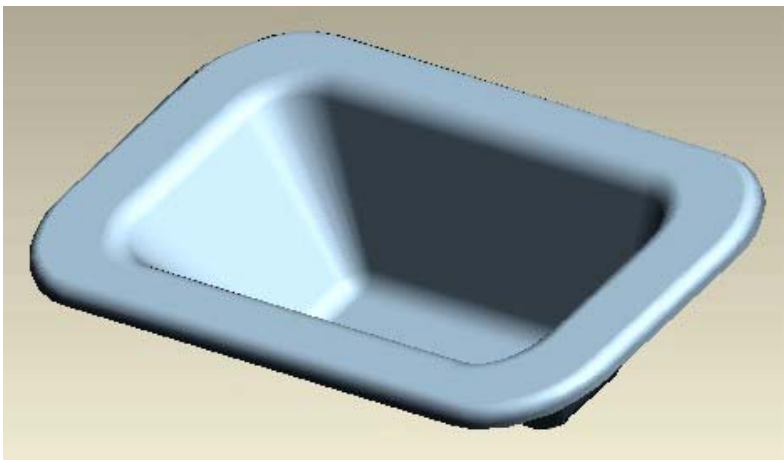


Figure 17 A test piece used in economical calculations

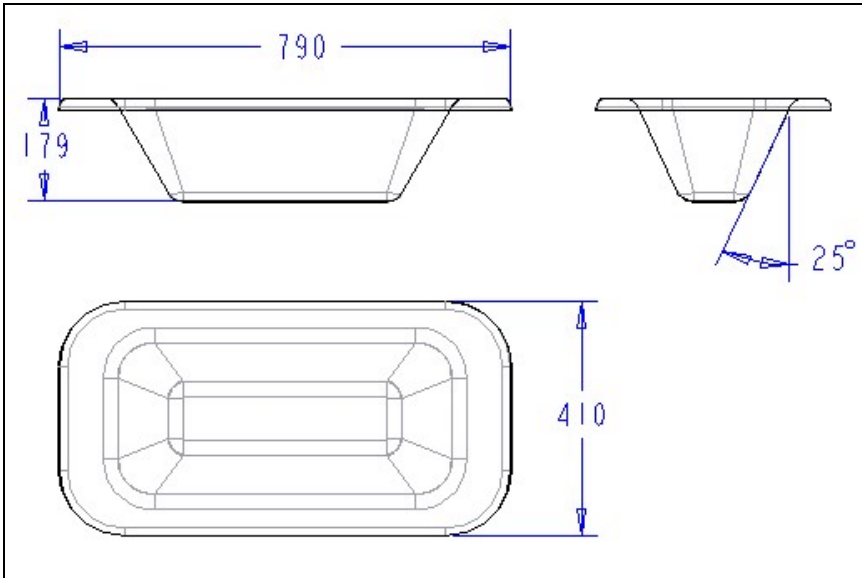


Figure 18 Dimensions of the test piece used in economical calculations

Comparison between these methods is based on estimated manufacturing cost. [34]

$$C = VC_{mv} + P_c \cdot R_c$$

where C_{mv} - cost of material per unit volume
 V - volume of material input to the process
 P_c - basic processing cost for an ideal part
 R_c - cost coefficient for the part design that takes into account shape complexity, surface finish and tolerances

In this case the cost of material is equal by deep drawing and incremental forming, and it can be left out of calculations.

The basic processing cost is given by

$$P_c = \alpha \cdot T$$

α - cost of operating a specific process; cost includes cost of machine and its services, labor and overheads.

T – cycle time

Cost of incremental forming

By calculating the cost of incremental forming we use two different sets of processing parameters: in first case parameters used in experimental work done in University of Saarland, and in second case parameters recommended by Amino factory.

First case of incremental forming: Processing parameters: horizontal forming speed 15 m/min, vertical feed 0.2 mm per step, total length of forming path 1465m.

Second case of incremental forming: Processing parameters: horizontal forming speed 30 m/min, vertical feed 0.5 mm per step, total length of forming path 585m.

Cost of setting up and NC programming is 50 EUR in both cases.
Cost of deep drawing dies has been estimated to be 12 800 EUR.

According to these processing parameters, the unit price per piece can be calculated. They are shown in Table 2. The costs are dependent on the cost of labour, electricity and other consumable cost that vary in each country.

Table 2. Comparison of deep drawing and incremental sheet forming parameters and unit costs

	Deep Drawing	Incremental forming 1	Incremental forming 2
Operating costs (EUR)	40	40	40
Parts per hour	40		
Cycle time (min)	1	1h 37 min	19,5
Part cost (without material)	1	64,8	13

According to these calculations, incremental forming is profitable if these kind of pieces are made less than 1000 parts. If the amount is over that, deep drawing is more profitable, when using the forming parameters recommended by Amino. If the research parameters are used, the break even point is earlier, in approximately 200 parts. Figure 19 shows a diagram of the costs in different number of parts.

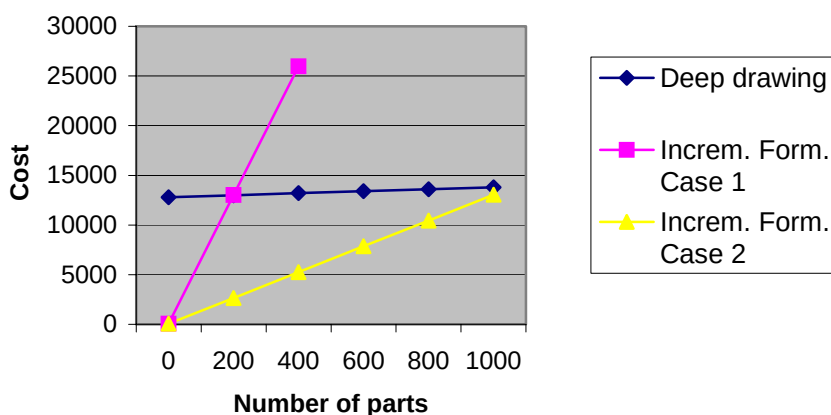


Figure 19 Cost comparison diagram for incremental forming and deep drawing

It should be noted that cost of production method is highly dependent on product geometry and can vary a lot. This calculation is an example and can be used as general reference, but it should not be applied to other kind of products without further research.

Hirt, Ames and Bambach [38] have been estimating the economic and ecological aspects of incremental forming, and had similar results.

3.2.4. Variations of incremental forming

Dieless NC forming is one variation of incremental forming. There are few other variations as well, that are being developed parallel to dieless NC forming.

Single point forming

Dieless NC Forming is sometimes called two point forming, because there are two contact points with the sheet, between the sheet and the forming tool and between the sheet and the support tool. In single point forming the support tool is eliminated and only forming tool is in contact with the sheet. The principle of the method is shown in the Figure 21.

Jeswiet has used a three-axis CNC mill together with CAM software to control the shaping tool [20], [37]. The sheet is clamped to a blankholder mounted on the mill bed. The metal shaping tool is a rounded rod, which is placed in the mill spindle. The blankholder remains stationary as the shaping tool pushes into the sheet, deforming it directly under the tool. During the forming, the tool lowers in small steps after each round.

In single point forming no support tools are used. In the beginning of the experiments, Jeswiet used support under the sheet, but as the work progressed, he found out that the supporting tool is not necessary. The form is created by computer controlled shaping tool movements.

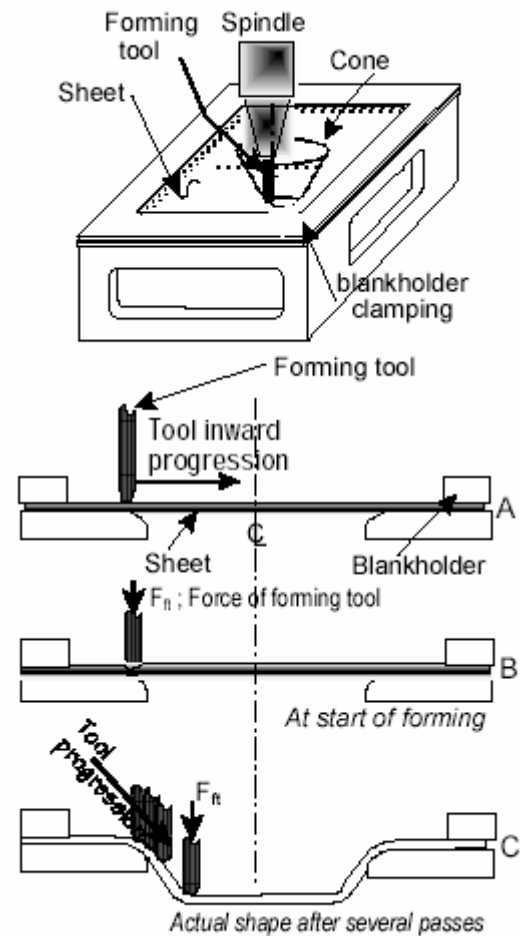


Figure 20 Single point forming (Jeswiet)

Incremental hammering

Hammering is perhaps the oldest form of sheet metal forming. Traditionally it is done manually using wooden positive die and hammer. The modern method of incremental hammering is to do it computer controlled by robots, without the support tool. The blank sheet is attached to a supporting frame and the forming tool is attached to an industrial robot. The robot punches the sheet into the designed form using circulating forming path and descending a small step on each round. The tool does not touch the sheet while moving on the x-y-direction. This disables the sheet stretching and twisting during the forming but affects also the surface quality of the product. An experimental incremental hammering setup is shown on the Figure 22.



Figure 21 Incremental hammering with an industrial robot

3.2.5. Applications

Dieless NC Forming is well suitable for producing single pieces and low volume series. It can also be used in prototyping and spare part production. The forming costs are about 5...10% of the costs of traditional pressing, but the production speed is also lower. Despite of the slower speed the method is more efficient when producing single parts or short series.

When using Dieless NC Forming in spare part production, remarkable saves can be achieved when storage for large moulds is not needed. The mould storing is a problem especially in car manufacturing industry, because the parts are large and the product life cycle is relatively long. This leads to long storage times and costs. New models are constantly developed and the number of moulds stored increases.

Dieless NC Forming enables producing different kind of products with the same machine without long setting times. The only product related part in the machine is the support tool, which is easy and quick to change. If the support tool is made of soft material such as wood or polymers, it is also quick and affordable to manufacture.

TAI Research Center in Helsinki University of Technology implemented a research project together with Finnish industry partners in 2002 to test the suitability of Dieless NC Forming on real production cases. The test results showed that the product geometry is important when considering the suitability of the method for certain product. The test parts in the project were real parts in production, and they were not designed for the method. This showed in the forming results as well. If the product is designed for the manufacturing method, the special requirements of the method can be taken in notice and the final result will be better. When applying the new method for old product, there are more difficult forms and other features that dilutes the method suitability for the product. These problems could be avoided by designing the products to meet the method limitations.

4. An application - Low volume production of aluminium boats

As opposed to the automotive production, production of boats is in most cases a typical low volume production. The design of the boat, or ship for that matter, is determined by their intended use, their sea-going properties, and by the general marked trends regarding shape and equipment. They are typically made from sheets or plates of various thicknesses, which are formed and joined, most often by welding. The sheet segments are usually joined to an underlying frame of profiles or plate components, and vary in shape from one segment to the next. The combination of flexibility in shape, adaptation to an underlying frame, and joining of adjacent segments represent a major challenge to the boat builders. In order to reduce the amount of adjustments after forming and thereby also reducing the presence of distortions after welding caused by residual stresses in the components, it is a goal to have low cost, accurate forming methods for producing sheet geometries in accordance with the specified geometry of the boat hull.

Based on these considerations forming of boats, and more specifically aluminium boats, were chosen as a case example in the project. The results are based on literature and internet searches, and a more detailed report is attached as Appendix 1. Further evaluation of the methods has be left for a later project. There are several producers of aluminium boats in the Nordic countries. One of them, the company Fjellstrand which has a long experience in producing aluminium high speed passenger boats, has participated in the project. Contacts have also been made to builders of other kinds of boats, e.g. fishing boats and boats used in the increasing aqua cultural area, e.g. fish farming.

The range of boats produced from aluminium is large, and the requirements concerning costs, weight and flexibility of shape varies extensively. One important category of aluminium boats is the light and

cheap leisure and fishing boats with limited requirements on design and which may be produced in medium sized production series. Another category is the group of robust Al boats that are made for special purposes, and which, of course, also may include larger fishing boats. Also here the requirements on shape are not the highest priority. As seen from the point of view of the aluminium industry and the boat builders there is an intention to increase the marked shares of smaller leisure boats and high-end yacht, cruisers and commercial passenger vessels. To increase within the leisure marked the boats must compete with those presently made from FRP (i.e. fibre reinforced plastics), which are materials that allows a high degree of shape flexibility. Even for the typically commercial boats, such as fishing boats and service boats in aquaculture, there may be seen an increasing design awareness which will favour those producers able to offer more flexible shaping of the boats.

The disadvantages originating from the problems of producing compound curved surfaces in a cost efficient way often outweigh the advantages coming from the lighter weight, the good durability and potential for recycling.

Today, some typical processes for forming of small numbers of aluminium sheets are stretch forming, hydraulic counter pressure forming or hydromechanical forming, warm press forming, superplastic forming, explosive forming and hot-blow forming. These methods still have their potential, but three areas of improvements should be addressed: The tooling costs should be reduced, the time for preparation, planning and set-up should be reduced, and process control and accuracy should be improved. These requirements point to the need for the application of (new) rapid tooling techniques, the need for efficient design and decision support systems, and a better control systems based on a knowledge of process and material behaviour.

There should also be a potential for using both single point and multi point forming methods with the appropriate design of tooling and control system. The lower part of the tooling may range from a single point of support, via the use of a matrix of numerically controlled pins (like ejector pins) to a complete lower die. The upper part of the tooling may also consist of a single point forming tool as in the Amino process, it may include a roll segment instead of the single point tool, or may be also an upper multi point tool which in principle may be as the one described for the lower part.

Whatever method is chosen there are a need for knowledge about the kinematics and interface conditions of the process, and the actual material behaviour for the given combination of process, tooling, material and product geometry. This knowledge also has to be presented in a form, e.g. in a computer program, so that it may be used by the producer as an aid in his day-to-day work.

5. Summary

Low volume production methods are already in use in many industry areas. Incremental forming is a new production method for sheet metal components, that brings several new possibilities into the sheet metal forming field. The geometries that previously were impossible or very expensive to prototype, are now possible to try. It is possible to make the prototypes from production material.

Incremental forming, as any other method, has its constraints. Geometrical limitations caused by the combination of sheet properties and process are the wall angle limitations and the restricted number of forming steps. The minimum rounding radius is a tool related limitation, and it can be developed further. Also the forming path can be developed to overcome some of the sheet related limitations such as wall angle.

When designing a product, the method and its limitations should be considered and the product should be designed for a certain method. If Dieless NC Forming is chosen as a manufacturing method, the product should be designed accordingly and the method limitations should be noticed in the design

process. This leads to more effective manufacturing and less iterations in the product development process.

At the moment part of the limitations are due to inadequate machine control and design. Tool marks could be reduced by changing the tooling path, but the control logic of the machines is not developed enough for changing the tooling path radically.

Dieless NC Forming has great potential as a tool in the product development process. It can be used for making prototypes, but also one-off parts and small series. The great advantage is that prototypes can be made of real material with real methods, and thus be tested as real products. Dieless NC Forming can also be combined with other forming methods when manufacturing prototypes or short series of products.

References

- [1] Multi-point forming: a flexible manufacturing method for a 3-d surface sheet, Li, M et al., Journal of Materials Processing Technology, 87, 1999, s 277-280
- [2] Iseki H., An approximate deformation analysis and FEM analysis for the incremental bulging of sheet metal using a spherical roller. Journal of Materials Processing Technology 111 (2001), pp 150-154.
- [3] Iseki H., Naganawa T., Vertical wall surface forming of rectangular shell using multistage incremental forming with spherical and cylindrical rollers. Journal of Materials Processing Technology 130-131 (2002), pp 675-679.
- [4] Dai K., Wang Z.R., Fang Y., CNC incremental sheet forming of an axially symmetric specimen and the locus of optimisation. Journal of Materials Processing Technology 102 (2000), pp 164-167.
- [5] Kim T. J., Yang D. Y., Improvement of formability for the incremental sheet metal forming process. International Journal of Mechanical Sciences 42 (2000), pp 1271-1286.
- [6] Shim M. S., Park J. J., The formability of aluminum sheet in incremental forming. Journal of Material Processing technology 113 (2001), pp 654-658.
- [7] Kim Y. H., Park J. J., Effect of process parameters on formability in incremental forming of sheet metal. Journal of Materials Processing Technology 130-131 (2002), pp 42-46.
- [8] Kim Y. H., Park J. J., Fundamental studies on the incremental sheet metal forming technique. Journal of Materials Processing Technology 140 (2003), pp 447-453.
- [9] Naganawa T., Advances in prototype and low volume sheet forming and tooling. Journal of Materials Processing Technology 98 (2000), pp 244-250.
- [10] Shima S. State of Art - Incremental Forming.
- [11] Strano M., Incremental forming processes: current and potential applications. Society of Manufacturing Engineers Technical paper. 2003.
- [12] *) Iseki H., Kato K., Sakamoto S., Flexible and incremental sheet metal bulging using a path-controlled spherical rollers. Trans. Jpn. Soc. Mech. Eng. C58 (1993) 3147-3155.
- [13] *) Iseki H., Kato K., Kumon.O, Ozaki K., Flexible and incremental sheet metal bulging using a few trolled spherical rollers. Trans. Jpn. Soc. Mech. Eng. C59 (1994) 2849-2854.

- [14] *) Nakajima N., Computerizing of traditional sheet metal forming. Trans. Jpn. Soc. Tech. Plasticity. 20 (1979) 686-700.
- [15] *) Hasebe T, Shima S. Study of flexible forming by hammering. J. Jpn. Soc. Tech. Plasticity 35 (1994) 1323-1329.
- [16] *) Matsubara S., Incremental backward bulge forming of a sheet metal with a hemispherical head tool. J. Jpn. Soc. Tech. Plasticity. 35 (1994) 1311-1316.
- [17] *) Kitazawa K., Wakabayashi A., Murata K., Seino J., A CNC incremental sheet metal forming method for producing the shell components having sharp corners. J. Jpn. Soc. Tech. Plasticity. 35 (1994) 1348-1353.
- [18] *) Kondo K., Mtsuzaki S., Hiraiwa M., Ohga K., Investigation of peen forming. J. Jpn. Soc. Mech. Eng. III 44 (1992) 3663-3672.
- [19] *) Matsubara M., Tanaka S., Nakamura T., Forming process of spherical surface by A CNC incremental press forming system. J. Jpn. Soc. Tech. Plasticity. 35 (1994) 1330-1335.
- [20] Jeswiet J., Incremental single point forming. Society of Manufacturing Engineers Technical paper. 2001.
- [21] Jeswiet J., Hagan E., Rapid prototyping non-uniform shapes from sheet metal using CNC single point incremental forming. Society of Manufacturing Engineers Technical paper. 2003.
- [22] Jeswiet J., Hagan E., Rapid prototyping of a headlight with sheet metal. Society of Manufacturing Engineers Technical paper. 2002.
- [23] Saotome Y., Okamoto T., An in-situ incremental microforming system for three-dimensional shell structures of foil materials. Journal of Materials Processing Technology 113 (2001), pp 636-640.
- [24] <http://www.esi-group.com/Products/Pamstamp/>, last accessed 12.09.2003.
- [25] <http://www.abaqus.com>, last accessed 12.09.2003.
- [26] Srinivasan T.M., Shaw J., Thompson K., Tubular hydroforming: results, SAE paper 980448, International Congress and Exposition, Detroit, MI, USA, February 1998.
- [27] <http://www.lstc.com>, last accessed 12.09.2003.
- [28] Koc M., Altan T., Application of two dimensional (2D) FEA for the tube hydroforming process, International Journal of Machine Tools & Manufacture 42 (2002) 1285–1295.
- [29] Hwang Y. M, Altan T. Finite element analysis of tube hydroforming processes in a rectangular die, Finite Elements in Analysis and Design 39 (2002) 1071–1082.
- [30] <http://www.deform.com/>, last accessed 12.09.2003.
- [31] Duan X., Sheppard T., Shape optimization using FEA software: a V-shaped anvil as an example, Journal of materials Processing Technology 120 (2002) 426-431.
- [32] <http://www.marc.com/>, last accessed 12.09.2003.
- [33] Hirt, G., Junk, S., Wituski, N. Surface quality, geometric precision and sheet thinning in incremental sheet forming. In: Materials week 2001, 1.-4. October 2001, Munich, Germany. Werkstoffwoche-Partnerschaft GBr.
- [34] K.G Swift and J.D.Booker, op.cit.;also A.J.Allen and K.G.Swift, *Proc. Instn, Mech. Engrs.*, vol 204, pp. 143-148, 1990.



- [35] Sawada, T., Matsubara, S., Sakamoto, M., Fukuhara, G. Deformation analysis for stretch forming of sheet metal with CNC machine tools. In: Geiger, M. (ed.) Advanced technology of Plasticity, Vol II. Proceedings of the 6th ICTP, September 19-24, Nürnberg, Germany, 1999. p. 1501-1504. ISBN 3-540-66066-6.
- [36] G. Hirt ,S. Junk, N. Witulski (Germany). Incremental Sheet Forming: Quality Evaluation and Process Simulation
- [37] J. Jeswiet, E. Hagan, A. Szekeres. Forming parameters for incremental forming of aluminium allow sheet metal. Proceeding of the I.MECH E Part B Journal Engineering Manufacture, Vol. 216, pp 1367-1371
- [38] Hirt, G; Ames, J; Bambach, M; Economical and ecological benefits of CNC incremental sheet forming; 1st IMEKO TC 19 Conference on Environmental Measurements, 13-17 October 2003 – Budapest, Hungary

*) in Japanese language

Attachments

1. SINTEF's report on aluminium boats